# THE EFFECT OF MARKER PLACEMENT ERROR ON THE INTERPRETATION OF INTER-LIMB DIFFERENCES IN FRONTAL PLANE KNEE LOADING DURING A CHANGE OF DIRECTION TASK

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Inter-limb differences in frontal plane knee loading have been observed during change of direction tasks following anterior cruciate ligament reconstruction. Assessment of these differences may be a useful means of monitoring rehabilitation, but their robustness to methodological sources of error such as marker placement is unclear. The aim of this study was to determine the effect of marker placement on the interpretation of inter-limb differences in frontal plane knee loading during change of direction. Participants completed a 90° change of direction task. Simulated displacements were applied to the lateral thigh, femoral epicondyle and tibia markers. Inter-limb differences in peak knee abduction moment were calculated in each condition. A 95% confidence interval of ± 0.52 Nm/kg was identified for knee abduction moment inter-limb differences. Marker placement limits the ability to identify small changes in inter-limb differences over repeated tests.

**KEYWORDS:** marker placement, change of direction, anterior cruciate ligament.

**INTRODUCTION:** Following anterior cruciate ligament reconstruction (ACLR), inter-limb differences in kinetic measures have been associated with negative long-term outcomes, such as the development of osteoarthritis and secondary injury (Wellsandt et al., 2016; Paterno et al., 2010). Inter-limb differences in frontal plane knee loading observed post ACLR during change of direction (CoD) tasks may thus be relevant in the context of rehabilitation and return to play decision making (King et al., 2018). Frontal plane knee loading is considered a key risk factor for injury, while CoD is reported as the most common mechanism of injury (Hewett et al., 2005; Alentorn-Geli et al., 2009). To use objective measures of inter-limb differences in frontal plane knee loading as means of monitoring rehabilitation, the metrics of interest must be reliable and robust to methodological sources of error such as marker placement.

The conventional gait model (CGM) is a marker-based biomechanical model commonly used in the analysis of lower limb movement tasks (King et al., 2018; Stearns et al., 2013). In the CGM, the anterior/posterior positions of the lateral thigh (THI), lateral femoral epicondyle (KNEE) and lateral tibia (TIB) markers all influence the calculation of kinetic measures at the knee (Kadaba et al., 1989). Previous work examining the effect of these marker positions on model outputs is yet to account for the inherent randomness to be expected in real world marker placement, focusing instead on systematic displacements (Groen et al., 2012; Holden and Stanhope 2005). Intra-tester variability in the positions of the THI, KNEE and TIB markers ranges from 2.3 – 12.2 mm (Della-Croce et al., 1999). Establishing how random marker displacements within or bordering on these ranges effects the ability to reliably identify and track changes in inter-limb differences is necessary prior to any clinical implementation. Thus, the aim of this investigation was to determine the effect of random marker displacements on the interpretation of inter-limb differences in frontal plane knee loading during a CoD task.

**METHODS:** Forty-seven male participants aged 18-35 (mean ± SD: 24.8 ± 4.8, height 180 cm ± 6 and mass 84 kg ± 15.2) approximately 9 months (8.7 ± 0.7) post primary ACLR were recruited. A matched healthy cohort (NORM) of 52 male participants (23.4 ± 3.7, 182.86 cm ± 6.38, 1.91 kg ± 7.4) were also recruited. All participants completed three trials of a maximum effort 90°change of direction task in both directions. The task involved a 5 m sprint followed by a 90° cut off their contralateral limb, i.e. plant their left foot on the force plate to turn right, followed by a 2 m sprint to the finish line (King et al. 2018). A synchronised 10-camera optical motion capture (200Hz; Bonita B10, Vicon Motion Systems Ltd, Oxford, UK) and force plate (1000Hz; AMTI, MA, USA) system was used to record ground reaction forces and the positions of reflective markers placed on the body during the manoeuvre. Markers were placed in accordance with the Plug-in-Gait (PiG) marker set, Vicon's implementation of the CGM. Prior to testing, all participants completed a standardised warm-up routine involving jogging, squats and jumps.

Motion and force data were low-pass filtered using a fourth order bidirectional Butterworth filter (15 Hz) (Kristianslund et al., 2018). Peak knee abduction moment (KAM) in the first 20% of stance was extracted from each trial, with the mean of each participants' three trials used for further analysis. Inter-limb differences in KAM were calculated for ACLR and NORM participants respectively as:

$$KAM_{ACLRLimb} - KAM_{NonACLRLimb}$$

$$KAM_{Dom} - KAM_{Nondominant}$$

Dominance was defined as the participant's self-preferred kicking leg. We then aimed to simulate a scenario in which repeated testing sessions were conducted on our ACLR cohort, with random marker displacements introduced on each occasion. Natural movement variability was thus controlled for and the effect of marker displacements was investigated in isolation. One hundred simulated marker displacements were generated for each participant. In each simulation, the displacement *(d)* of each marker (THI, KNEE and TIB) on the CoD stance leg was drawn from a uniform distribution over the interval -15 mm > *d* > 15 mm. Based on previously reported intra-tester variability in anatomical landmark location, this range encapsulated a worst case scenario for marker placement (Della-Croce et al., 1999). Displacements were applied along the corresponding segment *x*-axis to simulate real-world positioning error. Inter-limb differences were recalculated in each condition as described previously, meaning that each participant had 101 inter-limb difference measures. These corresponded to the original inter-limb difference as well as one-hundred simulated inter-limb differences.

The effect of marker placement on inter-limb differences was examined using two analyses. First, the effect was quantified by subtracting each ACLR patients' original inter-limb difference from each of their simulated differences. Using the distribution of changes in inter-limb differences we defined 95% confidence intervals to allow us to estimate the minimal change in inter-limb difference we could reliably identify between repeated testing sessions. Secondly, to assess the effect on the ability to identify ACLR patients with large inter-limb differences in KAM relative to a normative cohort, each ACLR patient was classified as having "normal" or "abnormal" inter-limb differences based on the NORM group variability. ACLR patients whose original inter-limb difference was between ±2SD were classified as having "normal" inter-limb differences, while those with inter-limb differences >±2SD relative to the NORM group were classified as having "high" inter-limb differences. The percentage of participants whose classifications changed from their original and the number of misclassifications were calculated.

**RESULTS:** Results are presented in Fig 1 and Fig 2. The standard deviation in change in inter-limb difference was 0.26 Nm/kg. Based on this distribution we identified a 95% confidence interval of ± 0.52 Nm/kg for KAM inter-limb differences during CoD. The minimum change we could identify between repeated tests was 0.86 Nm/kg. Thirty-five (75%) participants maintained their original inter-limb difference classification, while twelve

(25%) participants' classifications changed on at least one occasion. The rate of classification change ranged from 1 – 67% (Fig 2B).

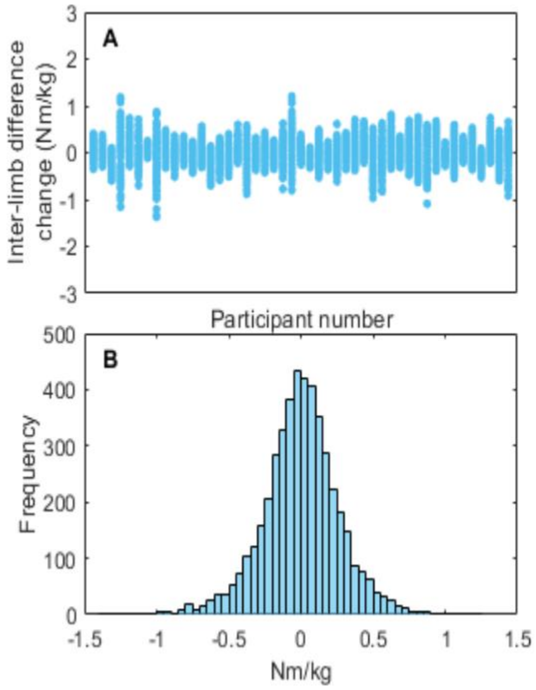


**Figure 1 (A).** Changes in inter-limb difference for each participant i.e. the difference between the original inter-limb difference and each simulated inter-limb difference. **(B)** Distribution of changes in inter-limb differences.

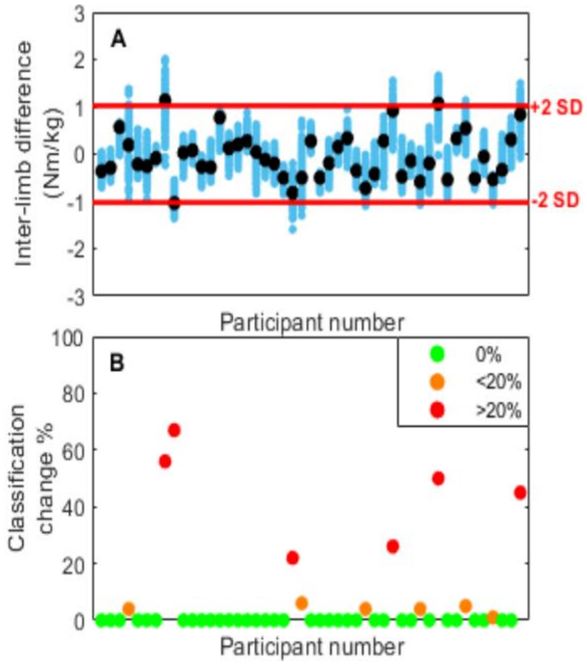


**Figure 2 (A).** ACLR inter-limb differences relative to NORM group variability. Black dots depict original ACLR inter-limb difference, blue corresponds to simulated inter-limb differences. Red lines depict SD thresholds for "normal" and "abnormal" classifications. **(B)** Percentage of occasions each participants' original classification changed from their original in each of the one-hundred simulations.

**DISCUSSION:** These findings highlight the inherent challenges in using the CGM and its variants in the assessment of inter-limb differences in KAM during CoD. We identified a 95% confidence interval of ± 0.52 Nm/kg in which we expect errors in KAM inter-limb difference measures to fall, as well as a minimal identifiable change in inter-limb difference of 0.86 Nm/kg. Mean group differences of 0.53 Nm/kg between ACLR and uninjured controls have been reported previously (Stearns et al., 2013). Though these differences were between groups as opposed to inter-limb, they indicate the magnitude of differences in KAM considered clinically relevant in the context of ACL injury. Our data indicate that there would be a 53.2% chance of identifying a change of this magnitude in individual KAM inter-limb differences between repeated tests due to error likely incurred from marker placement.

Despite the variation in measured inter-limb differences due to marker placement, 75% of our cohort maintained their original inter-limb difference classification throughout all one-hundred simulated trials (Fig 2A). 25% of participants changed classification from "normal" to "high" inter-limb differences or *vice versa* on at least one occasion. Participants with initially large inter-limb differences were more likely to be misclassified, given their original inter-limb difference was closer to the classification threshold. Combined with our minimal identifiable change in inter-limb difference of 0.86 Nm/kg, this would indicate that using the CGM to identify patients with abnormal inter-limb differences, and subsequently track the restoration of these differences to normative levels, is challenging in this context.

Alternative methods of modelling human movement have been developed in order to provide improved anatomical relevance compared to the CGM (e.g. CAST/6DoF approaches). While certain models have been shown to be reliable (Malfait et al., 2014), any alternative modelling technique that uses anatomical landmarks to define joint segment orientations continues to work on the assumption that marker placement is consistent and repeatable between practitioners (Charlton et al., 2004). Indeed, Groen et al., (2012) demonstrated that while implementing the optimized lower limb gait analysis model reduced errors due to marker placement during walking in certain variables, it also exacerbated those in others. Further research investigating the sensitivity of alternative modelling techniques across various movement tasks is warranted to inform their utility in assessing inter-limb differences.

**CONCLUSIONS:** We present an approach to quantify the minimal changes in inter-limb differences that can be reliably identified given realistic marker placement error and demonstrate that the variability resulting from these errors affects KAM inter-limb difference classifications in one in four participants. Whether or not these changes fall outside of what constitutes clinically relevant will be specific to the population, task and specific research question being investigated. Thus, these findings can be used in future research as a framework for both assessing the appropriateness of examining inter-limb differences within the context of the relevant study question, as well as interpreting the findings of past and future work.

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